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PERFORMANCE OF A SMALL HIGH-SPEED LIQUID JET APPARATUS

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Abstract: The performance of a small high-speed liquid jet apparatus is described. Water jets of 200m/s to 700 m/s have been obtained by firing a deformable lead slug from an air rifle into a stainless steel nozzle containing water sealed with a rubber diaphragm. Nozzle devices of using the impact extrusion (IE) method and cumulation (CU) method are designed to generate jets. The injection sequences are visualized using schlieren photography. The difference between the IE and CU methods in the jet generation is found.
Keywords: high-speed liquid jet, generation method, flow visualization

1. INTRODUCTION

High-speed liquid jets have important industrial applications and academic interests. Recently, Week et al.[1] have listed the applications of the jets in rain erosion, cavitation, jet cutting, diesel fuel injection, etc.. In the academic aspect, Shi and Takayama[2], Shi et al. [3] have emphasized that a supersonic liquid jet generator can be used as a fundamental tool in aerodynamics studies. In 1996, Shi and Itoh[4] reported the design and experiment of a small high-speed liquid jet apparatus that was based on Bowden and Brunton's method of firing a deformable lead slug from an air rifle into a stainless nozzle containing water sealed with a rubber diaphragm[5]. Because the slug directly impacts the nozzle to extrude the liquid flowing through a narrow orifice, the method is often called impact extrusion (IE) method or direct impact method. It has been known that the quality and behavior of the generated jets largely depend on the generation method or the design of the nozzle device. In the experiment of a high-pressure helium gas gun, Shi et al. [6,7] have demonstrated that a greater jet velocity can be obtained using the cumulation (CU) method, by which the liquid cylinder is firstly accelerated by the impact of a projectile and then the liquid is accelerated further after entering a converging nozzle. This paper will show an investigation by the flow visualization on that when the CU method is applied in the small high-speed liquid jet apparatus, what kind of the effect on the jet generation is.

2. EXPERIMENTAL DEVICES

Figure 1 shows the nozzle device of the IE method. A lead slug with 5 mm diameter, 6.7 mm length and 0.75 g mass impacts a stainless nozzle directly. The test nozzles contain about 150 mm^3 water and have 0.5 mm, 1 mm and 2 mm diameters respectively. The back end diameters of the nozzles are all 5.5 mm

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and the liquid is sealed with a 1 mm thick rubber diaphragm. The slug impacts the diaphragm and push the liquid to flow through the nozzle exit. The arrangement of fixing the nozzle in the nozzle holder has been shown in the figure. The nozzle is adjacent to a spacer ring and is pressed by a strangleholder screw. The spacer ring can adjust the distance between the nozzle and the screw. Figure 2 shows the nozzle device of the CU method. Now the nozzle is adjacent to a stainless cylinder in which 150 mm^3 water is sealed between a 9 μm thick Mylar film and a 1 mm thick rubber diaphragm. The nozzle and the cylinder are fixed in the nozzle holder by the strangleholder screw. The slug impacts on the diaphragm and push the liquid cylinder to enter the nozzle. After traveling through the nozzle, the liquid flows out of the nozzle exit to form a jet.

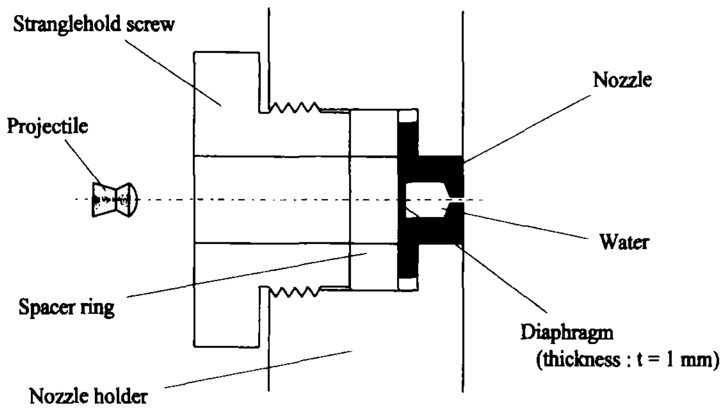

Fig. 1 Nozzle device for the impact extrusion (IE) method

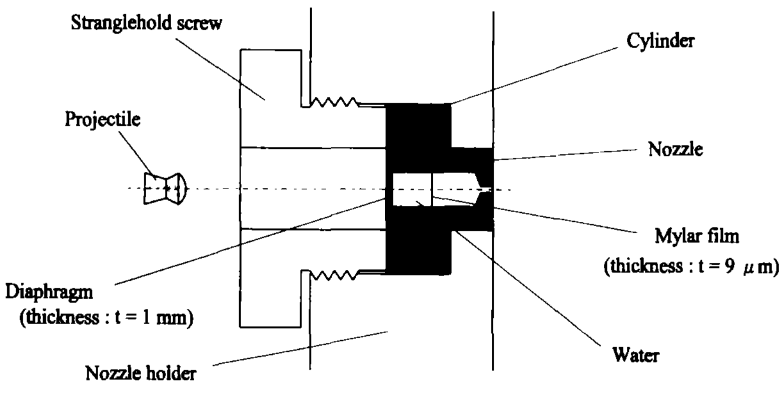

Fig. 2 Nozzle device for the cumulation (CU) method

3. RESULTS

Figures 3 and 4 give the schlieren photographs of the supersonic water jets from the 1 mm diameter nozzle at different stand-off distance by the IE and CU methods respectively. We firstly analyze the jets by the IE method shown in Fig.3. In accordance with the jet shape and its stand-off distance, the jets shown in Figs.3(e)~3(g) have about 15 mm stand-off distance. It is seen that when the jet is fully

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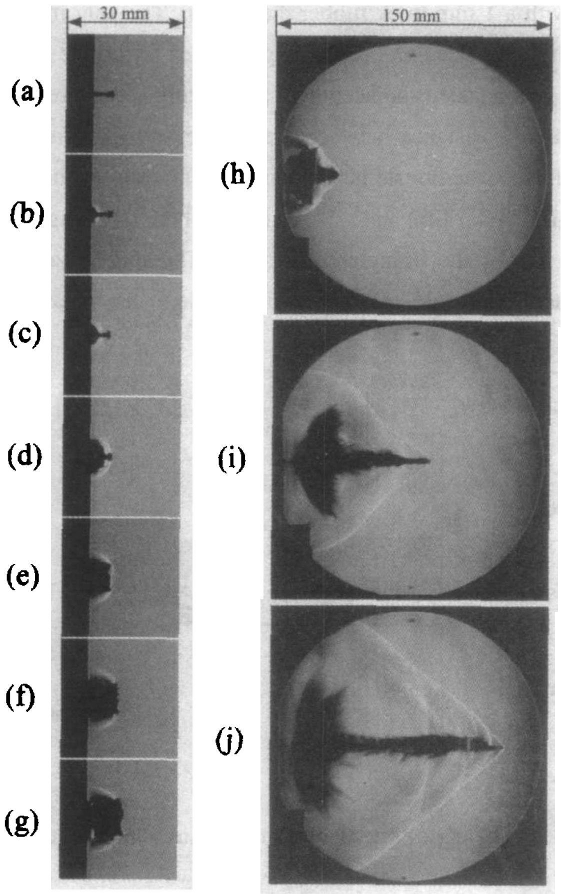

Fig. 3 Schlieren photographs of supersonic water jets from a 1 mm diameter nozzle.
IE method. The jet velocity is ca. 600 m/s

developed (Figs. 3(i), 3(j)), the jet has a sharp supersonic tip and a long stretched thin body which is surrounded by the bifurcated jets near the nozzle exit. The schlieren photography have revealed the mechanism of the formation of the bifurcated jets. From Figs.3(a)~3(h), it is seen that at the beginning, a thin jet of about 1 mm diameter appears at the nozzle exit (Fig.3(a)). Due to the multiple reflection of the shock wave in the nozzle[8], the successive liquid must flow out of the nozzle (Figs.3(b), 3(c)). The successive liquid impacts on the front jet head to cause the liquid to expand radially. The diameter of the spray head has been 13.3 mm. This is the so called liquid jet discontinuity[9]. The radial expansion brings about velocity reduction and quick atomization of the bifurcated jets so that central jet emerges from the spray (Fig. 3(h)) and moves forward (Figs. 3(i), 3(j)). The helical internal vortex and wave shape of the jet boundary shown in Fig. 3(j) are associated with the helical instability and the Kelvin-Helmholtz instability[10].

When the CU method is applied, the jet bifurcation disappears (see Fig. 4). Because the liquid has already got initial velocity before emanating from the nozzle exit, all the fluid particles move forward. This kind

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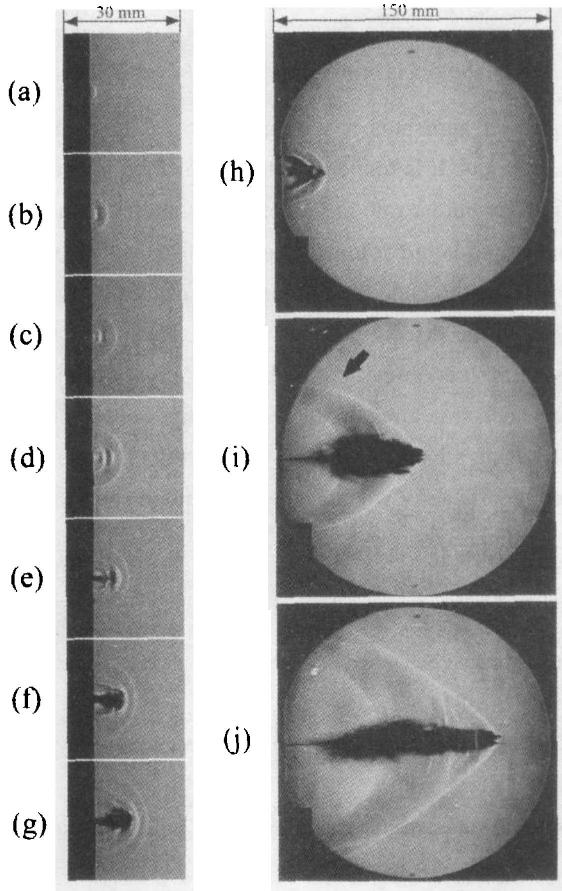

Fig. 4 Schlieren photographs of supersonic water jets from a 1 mm diameter nozzle. CU method. The jet velocity is ca. 600 m/s

of jet is easy to be atomized and disintegrated. It is evident that the expanded spray has been much larger than the nozzle diameter which is equal to the diameter of the thin liquid tail behind the spray. On the other hand, the diameter of the spray generated by the CU method is larger than that generated by the IE method. This shows the role of the CU method in the liquid disintegration and atomization. The disruption on each jet front is associated with the Rayleigh-Taylor instability[11]. The schlieren photographs have shown the complicated shock waves system induced by the jet. In Fig.4(a), the first appearing shock wave is the transmitted shock wave which is caused the impact on the liquid cylinder (see Fig. 3). Following the first shock wave, the second shock wave appears in Figs.4(b), 4(c), which is a blast wave caused by the sudden motion of the liquid in the nozzle. Then the third shock wave that is the bow shock around the supersonic liquid jet appears in Figs. 4(d)~4(f). Since the jet will overtake the first and second waves (Figs. 4(g)~4(j)), the bow shock will interact with these waves. In Fig. 4(i), the arrow marks the transmitted shock wave. It is seen from the schlieren photographs that not only the disruption of the jet head causes complicated wave structure (Fig. 4(i)), but also the wave shape of the jet boundary

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causes many Mach waves (Fig. 4(j)).

4. CONCLUSIONS

The small high-speed liquid jet apparatus has been performed to demonstrate various factors in the generation of supersonic water jets. It is found that the CU method is very effective in the disintegration and atomization of the liquid jet but its role in the jet acceleration depends on the impact momentum of the projectile, nozzle diameter and liquid volume. The flow visualization reveals that the jet bifurcation is often accompanied with the IE method and the bifurcation is caused by the interrupted acceleration of the liquid in the nozzle as well as the discontinuity of the jet. The jet by the CU method brings about a complicated shock wave system. It is observed that the disruption of the jet head and the discontinuity of the jet can cause some new shock structures. In the relationships between the jet velocity and downstream distance, the IE method shows an advantage to keep the jet velocity stable since only the jet velocity of 0.5 mm nozzle is decreased significantly whereas the CU method shows that both 0.5 and 1 mm nozzles reduce the jets velocities significantly.

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